



## A quantitative analysis of alginate swelling

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### ABSTRACT

The swelling behavior of physically cross-linked polysaccharides is not fully understood despite its significance in many applications such as drug delivery. In this study the swelling behavior of three types of alginate were characterized experimentally at various calcium concentrations. Additionally, equilibrium swelling data was analyzed in terms of Flory and rubber elasticity theories, which were developed for chemically cross-linked networks. This analysis suggested that these theories are not applicable for alginate. In particular, an increase in the number of monomeric units between cross-links was observed at a higher calcium concentration, whereas the theory predicts the opposite. The kinetics of the swelling process was also analyzed experimentally and theoretically. The experimental data was found to obey second-order kinetics. Moreover, a decrease in the swelling rate constant with elevated calcium concentration was observed. Lastly, it is indicated that the unusual swelling behavior of alginate could be attributed to a lateral chain association.

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### 1. Introduction

One of the well-known features of lightly cross-linked polymers is their ability to change their volume by up to many folds when exposed to an appropriate solvent. The swelling behavior of chemically cross-linked polymers was extensively studied both experimentally and theoretically (Flory, 1953; Tanaka, 1978; Tanaka et al., 1980). On the contrary, the swelling behavior of physically cross-linked polyelectrolytes, such as polysaccharides (e.g. alginate and chitosan) and acrylates cross-linked with  $Al^{+3}$  (Sato, Hirashima, Suzuki, Goto, & Tokita, 2005), has not been fully explored, although it is believed to significantly affect many properties, such as the ability to establish bioadhesion interactions (Baloglu, Ozyazici, Hizarcioglu, & Karavana, 2003; Richardson, Dettmar Peter, Hampson Frank, & Melia Colin, 2004), mechanical strength (Feng & Pelton, 2007), drug release ability (Pillay & Fassihi, 1999; Ramirez Rigo, Allemandi, & Manzo, 2006), permeability (Morch, Donati, Strand, & Skjaak-Braek, 2006), and degradation rate (Pillay & Fassihi, 1999).

Alginate is a widely studied water-soluble polysaccharide consisting of alternating segments of 1 → 4 linked  $\alpha$ -L-guluronic acid (G) and  $\beta$ -D-mannuronic acid (M) (Draget, 1997; Draget, Oestgaard, & Smidsroed, 1990; Draget, Skjak-Braek, & Smidsrod, 1997). The proportion and distribution of these segments, along with their

relative sequencing, determines the chemical and physical properties of the alginate (Batchelor et al., 2002). Alginate gels are used in many pharmaceutical applications, such as wound dressing, control release drugs, and immobilization matrices for cells or other materials (Deckwer, 2005). Alginates displays an affinity toward multivalent cations such as  $Ca^{+2}$  and is able to bind those ions selectively and cooperatively (Draget et al., 1997), a process which leads to the formation of ionically (i.e. physically) cross-linked alginate gels (Draget, 1997). The affinity of alginates to ions depends generally on the chemical composition and specifically on the number and length of the guluronic residues (G-blocks) (Draget, 1997; Draget et al., 1997). It is commonly assumed that the polymer's affinity to multivalent cation is exclusive to the guluronic blocks (Deckwer, 2005). However, a recent study suggested that MGM blocks are also involved in the creation of the alginate network (Donati et al., 2005).

The swelling behavior of alginate was studied experimentally by several groups (Kong, Lee, & Mooney, 2003; Martinsen, Skjaak-Braek, & Smidsroed, 1989; Pillay, 1999; Richardson et al., 2004; Roger, Talbot, & Bee, 2006). Those studies have shown that an increase in the calcium concentration reduces the degree of swelling (Kong et al., 2003; Martinsen et al., 1989; Roger et al., 2006). In addition, low swellability was observed in an acidic environment (Pillay, 1999).

A much less documented behavior of alginate is its syneresis, a macroscopic phenomenon characterized by a slow time-dependent de-swelling of a gel resulting in an exudation of liquid. Syneresis is commonly observed in various food systems (Draget et al., 2001), for example in milk proteins undergoing sol/gel transition in the course of yoghurt or cheese production. However, a systematic examination of this phenomena is still absent (van Vliet,

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Lakemond, & Visschers, 2004). One of the first publications that detected a shrinkage in alginate gel ascribed it to water evaporation or intermolecular interactions leading to water exudation (Miller, 1975). Draget et al. (1990) found that syneresis is strongly related to the amount of calcium present in the gel. In particular, syneresis became prominent when the calcium content exceeded the amount of guluronic acid residues in the gel. Later work by the same group revealed a relation between the alginate molecular weight, the flexibility of the elastic segment, and the degree of syneresis (Draget et al., 2001). It was claimed that low molecular weight chains created a more rigid structure, which prevented further contraction of the gel, thus leading to a low degree of syneresis. On the other hand, the more flexible and elastic segments allowed rapid relaxation, further facilitating the contraction and high degree of syneresis (Draget et al., 2001). Donati et al. (2005) concluded that long MG/MG alternating sequences are responsible for the gel syneresis. It appears that secondary MG/MG junctions induce a partial collapse of the gel network, leading to a notable decrease in the storage modulus. Swelling/de-swelling transitions of alginate gels were studied by Saitoh, Araki, Kon, Katsura, and Taira (2000). Swollen alginate samples were immersed in different types of solutions containing nonelectrolyte solutes, monovalent and divalent metallic salts. The presence of divalent metallic cation was found to induce shrinkage, believed to be caused by the formation of additional cross-linking junctions in the gel.

The objective of the current study was to quantify the swelling and the syneresis phenomena of alginates. Experimental equilibrium swelling results were analyzed using known swelling theories, previously developed for covalently cross-linked networks, and the applicability of these theories to alginates was investigated. In addition, the swelling kinetics of two types of alginates was studied for the first time. These measurements provided additional insight into alginate's swelling mechanism.

## 2. Materials and methods

### 2.1. Materials

Sodium alginate was kindly provided by FMC-Biopolymers (Norway) and used as received. Three different alginate types were used: LF200S (65–75% guluronic acid), HF120RBS (45–55% guluronic acid) and LF240D (30–35% guluronic acid). Calcium carbonate was purchased from Sigma and used without further purification. D-(+)-Gluconic acid  $\delta$ -lactone (GDL) was purchased from Fluka and used as received. Double distilled water was used for the swelling experiment.

### 2.2. Molecular weight determination

The average molecular weight was calculated from the Mark-Houwink equation

$$[\eta]_{\text{int}} [\text{mL/g}] = K \cdot M^a$$

where  $M$  is the molecular weight of the polymer,  $\eta_{\text{int}}$  is the intrinsic viscosity, and the constants  $K$  and  $a$  for alginate samples are  $K = 4.85 \times 10^{-3}$  and  $a = 0.97$  (Stokke et al., 2000).

Ubbelohde viscometer was used to determine the specific viscosity  $\eta_{\text{sp}}$  and the relative viscosity  $\eta_r$  of diluted alginate solutions in 0.1 M NaCl at 20 °C. The intrinsic viscosity was determined by extrapolating the  $[\eta_{\text{sp}}]/C$  vs.  $C$  curve and the  $(\ln \eta_r)/C$  vs.  $C$  curve to zero, and averaging the value of the intercept.

### 2.3. Gel tablets preparation

Homogeneous gel tablets were prepared using an internal setting technique (Draget, 1997; Draget et al., 1990). A 10 mg/ml alginate solution was mixed with  $\text{CaCO}_3$  powder followed by the addition of D-glucono- $\delta$ -lactone (GDL) solution at a 2:1 M ratio of GDL: $\text{CaCO}_3$ . The alginate and GDL solutions were mixed at a ratio of 1:1 to create a final alginate concentration of 5 mg/ml with varied  $\text{CaCO}_3$  concentration. Hundred microliters of the final solution was poured into a circular mold and left for approximately 1 h to complete gelation.

### 2.4. Swelling experiment

The kinetics of alginate swelling was characterized by placing alginate tablets ( $n=6$  for each calcium concentration) in water and by measuring the weight of each tablet periodically. The tablets were placed on a stainless steel grid positioned inside a petri dish containing 50 ml DD water. Each series (at an identical calcium concentration) was placed in a separate dish. During the experiment the dish was covered in order to minimize water loss due to evaporation. Each tablet was weighed separately, and the weight of all tablets having the same calcium concentration was averaged. After weighing, the tablets were placed back into the petri dish.

Equilibrium swelling was determined using the same method explained above, but the tablets were weighted only twice: once at the beginning of the experiment ( $t=0$ ) and once after achieving equilibrium ( $t=24\text{h}$ ). The reported values are the averages of 12 tablets.

### 2.5. Mechanical properties

Young's modulus ( $E$ ) was measured using ARES (Advanced Rheometric Expansion System) instrument. Force gap experiments were used, and the Young's modulus was calculated from the slope of the normal force compression curve at low strain values. The measurements were performed on tablets obtained from the equilibrium swelling experiment after the final weighing ( $n=12$ ). The shear modulus ( $G$ ) was calculated from the relationship (Colby & Rubinstein, 2003)

$$E = 2(\nu + 1)G \approx 3G \quad (1)$$

where  $\nu$  is the Poisson ratio.

## 3. Results and discussion

### 3.1. Polymer molecular weight

The chemical composition of the alginate samples as obtained from the manufacturer, and its molecular weight determined by the intrinsic viscosity, are summarized in Table 1. As demonstrated, the samples are diverse in G content, but are very similar in molecular weight. As a result, changes in the swelling behavior and mechanical properties resulting from different calcium concentrations can be related to variations in the G content.

**Table 1**  
Characteristics of the studied alginate samples.

Alginate sample	G content (%)	$[\eta]_{\text{int}}$ [mL/g]	$M$ [g/mol]
LF200S	65–75	364.82	$1.06 \text{ E} + 05$
HF120RBS	45–55	287.65	$8.33 \text{ E} + 04$
LF240D	30–35	355.11	$1.04 \text{ E} + 05$

### 3.2. Equilibrium swelling

Fig. 1 displays equilibrium swelling ratios as a function of the calcium concentration for three different alginate types. Although for some samples  $Q > 1$  (swelling), and for others  $Q < 1$  (syneresis), all points belonging to the same alginate type seem to collapse into a single curve. This observation suggests that the terms “swelling” and “syneresis” (de-swelling), in fact describe the same physical phenomenon, as is the case for chemically cross-linked polymers. Indeed, each data set could be empirically fitted to a power law model using the form  $Q = A[Ca]^n$  with a single exponent, where the empirical parameters  $A$  and  $n$  are listed in Table 2. All alginate types display a similar power value, which could further suggest that all types share the same swelling mechanism. In agreement with previous works (Kong et al., 2003; Omidian, Rocca, & Park, 2006; Stokke et al., 2000), a reduction in the swelling ratio is observed when the calcium concentration is increased. Similar to the findings of Stokke et al. (2000) and Draget, Skjaak-Braek, Christensen, Gaaseroed, and Smidsroed (1996), increased  $G$  content also reduces the swelling ratio. However, Kong et al. (2003) did not find any correlation between the  $G$  content and the swelling ratio.

A gel swells when an external pressure (i.e. swelling pressure) is applied by the solvent. At equilibrium the swelling pressure becomes equal to zero due to a balance between two opposing tendencies: the ordinary gain in entropy resulting from the mixing of the polymer and the solvent, and the decrease in entropy due to distortion (i.e. expansion) of the network (Flory, 1944; Katchalsky, 1954). The ratio between the gel volume at equilibrium  $V_{eq}$  and the volume of the dry polymer  $V_{dry}$  can be calculated using the mean field theory and statistic thermodynamics. For gels in a good solvent, this ratio takes the form (Colby & Rubinstein, 2003)

$$\frac{V_{eq}}{V_{dry}} \approx \frac{N^{\frac{3(3\nu-1)}{4}}}{\phi_0^{0.25}} \cdot \left(\frac{\nu}{b^3}\right)^{\frac{9(2\nu-1)}{4}} \quad (2)$$

where  $N$  is the number of repeating units between cross-links,  $\phi_0$  is the volume fraction of the polymer with respect to the total volume of the as-prepared gel  $V_0$ ,  $b$  is the Kuhn length,  $\nu$  is the excluded volume and  $\nu$  is Poisson's ratio [dimensionless]. Multiplying both sides of Eq. (2) by  $\phi_0$ , and using a value of  $\nu \cong 0.588$  one gets

$$Q \approx \left(\frac{\nu}{b^3}\right)^{0.4} \cdot N^{0.57} \phi_0^{0.75} \quad (3)$$

where the equilibrium swelling ratio  $Q$  is defined as the ratio between the gel volume at equilibrium and the volume of the as-prepared gel.

**Table 2**

Fit parameters to a power law model describing the dependence of the swelling ratio on the calcium concentration.

Alginate type	$A$	$n$
LF240D	6.556	−0.509
HF120	3.795	−0.472
LF200S	3.175	−0.491

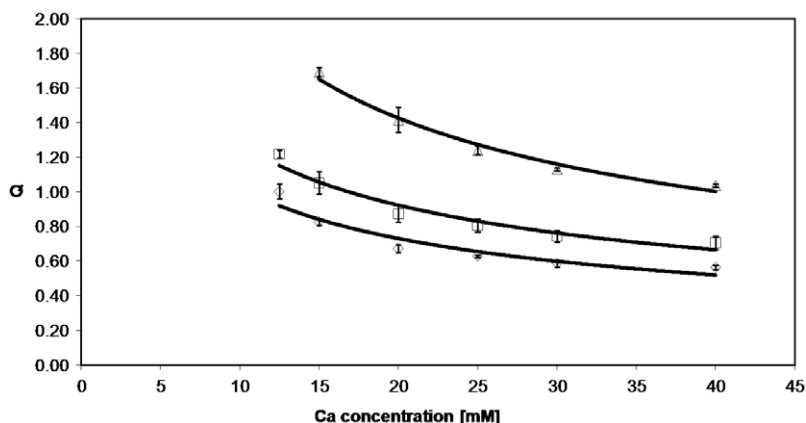
As pointed out by Velings and Mestdagh (1995), volume changes in alginate gels can be correlated to changes in its mass due to mere polymer movement. A linear correlation exists between the volume and the weight changes with a slope of 1.08 kg/l, which is close to the value of water density at room temperature. Therefore, equilibrium swelling ratios could be determined from the ratio of the mass of the alginate tablet at equilibrium to its initial mass.

Eq. (3) expresses the swelling ratio as a function of the degree of polymerization between cross-links, while the available experimental data shows the calcium concentration. The “egg-box” model (Stokke et al., 2000) has interpreted the cross-linking as a near-neighbor, auto-cooperative process when additional binding of the same ion becomes more favorable (Draget, 1997). Therefore, the use of a linear relationship between the calcium concentration and the degree of polymerization is not necessarily valid in this case, and an independent estimate into the degree of polymerization between cross-links is required. For chemically cross-linked gels, it is possible to relate the degree of polymerization between cross-links  $N$  to the shear modulus  $G$  using a relation derived from the rubber elasticity theory (Colby & Rubinstein, 2003; Mitchell, 1980; Treloar, 1975; van Kleef, Boskamp, & van den Tempel, 1978)

$$G = \frac{1}{N} \frac{c}{M_w} RT \quad (4)$$

where  $c$  is the polymer concentration,  $M_w$  is the monomer's molar mass,  $R$  is the low gas constant and  $T$  is the temperature. The shear modulus in Eq. (1) is often calculated from the Young modulus  $E$  as  $G \approx E/3$  (Colby & Rubinstein, 2003) assuming that  $\nu$  is equal to 0.5 (Wanga, Cowen, Zhang, & Thomas, 2005). It should be noted that to the best of our knowledge, the validity of Eq. (4) to alginates was never explicitly examined.

In order to assess the validity of Eq. (4), measurements of the shear modulus of the gels in their equilibrium-swollen state is required. The results of these measurements are summarized in Fig. 2. Interestingly, the Young's modulus of alginate samples with high and intermediate  $G$  content decreases when increasing the calcium concentration. However, for the alginate with the low  $G$



**Fig. 1.** Equilibrium swelling ratios. (◇) Alginate LF200S, ca 70%  $G$  (□) Alginate HF120, ca 50%  $G$  (△) Alginate LF240D, ca 30%  $G$ . Solid lines represent fits to a power law model; the fit parameters are summarized in Table 1.

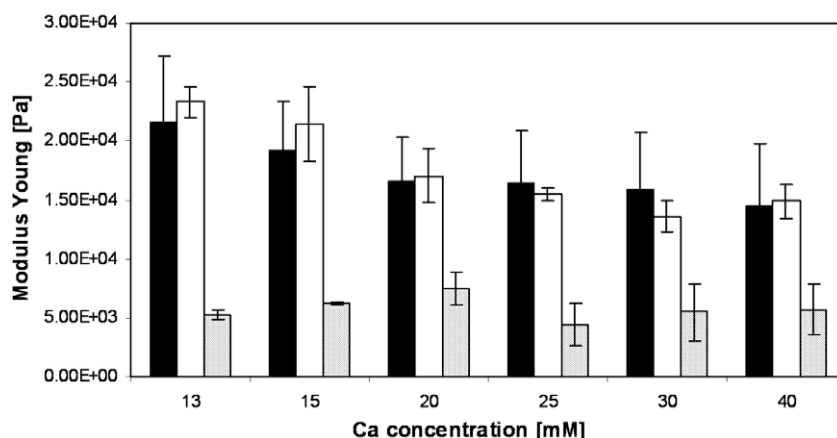


Fig. 2. Young's modulus as a function of calcium ion concentration. (■) Alginate LF200S, ca 70% G (□) Alginate HF120, ca 50% G (▒) Alginate LF240D, ca 30% G.

content there is no significant change in Young's modulus when the calcium concentration is altered. Identical results were obtained when the modulus was evaluated by compressing experiments performed using a tensile machine (data not shown). Temple et al. (Segeren, Boskamp, & Van den Tempel, 1974) found that at low swelling ratios, the modulus increases with an increase in the swelling ratio. Presenting the data shown in Fig. 2 in terms of  $G$  vs.  $Q$  showed this observation corresponds with our findings (data not shown). We note that the relation between the Young's modulus and the calcium concentration seems to vary depending on the experimental conditions. Kong et al. (2003) characterized non-swollen alginate gels and found that higher  $\text{Ca}^{+2}$  concentrations and high  $G$  content leads to an increase in the Young's modulus. Donati et al. (2005) detected a similar trend at low calcium concentration, however, at  $\text{Ca}^{+2}$  concentrations higher than 20 mM a reverse tendency was observed. This phenomenon was related to a possible partial collapse of the network upon calcium induced "zipping" of long alternating blocks, which leads to junction zones conjugation.

Further analysis using Eq. (4) was performed to estimate the number of segments between cross-links  $N$ . The results are presented in Fig. 3 as a function of calcium concentration. The average number of monomeric units between cross-links is about 10–40, in agreement with the previously reported values of thirty monomers (Mitchell & Blanshard, 1976) and eleven monomers (Segeren et al., 1974). Yet, an increase in the value of  $N$  with elevated cross-link concentration is observed. There are several possible explanations

to this unusual behavior. One option is that the rubber elasticity theory is not valid for alginate gels. The literature dealing with this question is controversial. Temple and co-workers (Segeren et al., 1974) identified several features of alginate gels that were consistent with the classical theory of rubber elasticity, for example, a positive temperature dependence of the storage modulus and a low loss factor ( $G''/G'$ ) (Moe, Draget, Skjak-Braek, & Smidsrod, 1992). In addition, an agreement was found between the value of  $N$  calculated from the storage modulus using Eq. (4) and the value calculated from swelling measurements. However, a non-linear stress-strain curve at relatively low strain values, and an increase in the storage modulus upon swelling was also observed, which can allude to non-rubber-like behavior. Mitchell and Blanshard (1976) have also employed the rubber elasticity theory, yet mention that there are some uncertainties about its validity. More recent studies have disqualified the use of the rubber elasticity theory for alginate gels due to its unique cross-linking structure (Andresen & Smidsroed, 1977; Mitchell, 1980; Mitchell & Blanshard, 1976). Mitchell and co-workers (Mitchell, 1980; Mitchell & Blanshard, 1976) suggested that the degree of cross-linking influences the gel behavior. At low degree of cross-linking the network chains will be longer and have a greater chance of showing rubber-like behavior, while at high degree of cross-linking the network chain will be much stiffer, and the rubber elasticity theory will not hold. Another possible explanation can be attributed to the "egg box" structure of alginate gels and more specifically to the cooperative pairing of contiguous guluronate residues (Grant,

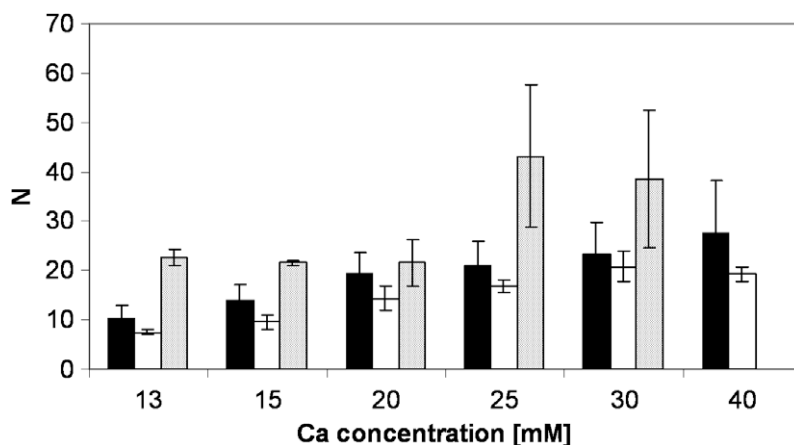


Fig. 3. Number of segments between cross-links  $N$  estimated using Eq. (4) from modulus measurements of swollen alginate gels. (■) Alginate LF200S, ca 70% G (□) Alginate HF120, ca 50% G (▒) Alginate LF240D, ca 30% G.



Morris, Rees, Smith, & Thom, 1973; Stokke et al., 2000). The affinity of alginate chains toward divalent ions increases with their concentration in the gel (Deckwer, 2005). This phenomenon has been interpreted as a near-neighbor auto-cooperative process when additional binding of the same ion becomes more favorable (Draget, 1997). Such behavior can lead to lateral association of alginate chains, which was detected using small angle X-ray scattering (SAXS) measurements (Stokke et al., 2000; Yuguchi, Urakawa, Kajiwar, Draget, & Stokke, 2000) and fiber X-ray diffraction (Li, Fang, Vreeker, Appelqvist, & Mendes, 2007; Sikorski, Mo, Skj-Brk, & Stokke, 2007). The lateral association of chain segmentation was found to depend, among other factors, on the G-block content and cross-linked concentration  $[Ca^{+2}]$ . This can eventually reduce the total number of macroscopic junction zones that can be detected by modulus measurements. Therefore in samples with low G content, the effect of lateral association is insignificant and does not affect macroscopic properties, such as the modulus. This mechanism is in line with the one suggested by Donati et al. (2005), which attributed the modulus decrease to a partial collapse of the gel network due to junction zone conjugation.

We attempted to formulate a quantitative relation between the swelling ratio and the cross-linking density. Clearly, since the swelling ratio decreases with increased calcium concentration while  $N$  increases, Flory's theory (Eq. (5)) does not hold for the studied alginate gels. Developing a new theoretical equation is beyond the scope of this work. However, an empirical power law correlation is given in Fig. 4 and Table 3. The entire data set could be described using a single equation. Therefore, it stands to reason that the swelling and the de-swelling are governed by the same mechanisms and only the initial state of preparation, (i.e. water content), which is lower or higher than the water content at equilibrium, will determine whether the gel will swell or de-swell.

Increasing the calcium concentration has led to a reduction in the swelling ability, as well as in its mechanical strength. Apparently, at higher calcium concentrations there are less junction zones. However, there seems to be larger numbers of chains associated in each one of them having an element that could decrease the chain flexibility. While the polymer chains integrate to create the associated junction zone, their rubber-like resistance to stretching increases and overpowers the mixing entropy of the polymer, promoting solvent molecules to accumulate. Therefore, the gel swells to a lesser degree.

### 3.3. Swelling kinetics

The swelling kinetics of two alginate types is presented in Fig. 5. The samples exhibit both swelling and syneresis (de-swelling) depending on the G-content and the  $Ca^{+2}$  concentrations.

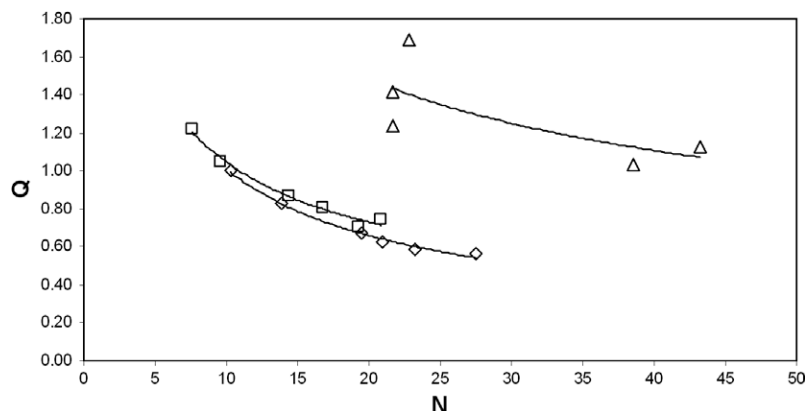


Fig. 4. The relation between experimental swelling ratio and the number of segments between cross-links  $N$  estimated by using Eq. (4) for ( $\diamond$ ) Alginate LF200S, ca 70% G ( $\square$ ) Alginate HF120, ca 50% G ( $\triangle$ ) Alginate LF240D, ca 30% G. The solid lines represent fits to Eq. (3); fit parameters are summarized in Table 2.

Table 3

Fit parameters for the curves shown in Fig. 4.

Alginate type	Pre-factor	$n$
LF240D	178.2	-0.476
HF120	123.3	-0.518
LF200S	288.2	-0.614

An interesting observation is a local maximum observed at short times at low  $Ca^{+2}$  concentration. A similar maximum was also detected for polyacrylamide/poly( $N,N$ -dimethylacrylamide)/poly( $N$ -isopropylacrylamide) networks that were first chemically cross-linked by radical polymerization and further physically cross-linked with Laponite nanoparticles (Can, Abdurrahmanoglu, & Okay, 2007). The maximum shifted to shorter times upon increases in the chemical cross-links density at a constant density of particles.

The swelling kinetics of alginate gels was investigated by several groups (Draget et al., 1996; Martinsen et al., 1989; Pillay, 1999; Ramirez Rigo et al., 2006; Richardson et al., 2004; Roger et al., 2006), but to the best of our knowledge has yet to be quantified. Draget et al. (1996) showed that both the molecular weight and the bead size affect the swelling kinetics of high G alginic acid gels. However, the swelling of low G gels is less sensitive to these parameters. Martinsen et al. (1989) referred to the swelling behavior as the "gel beads resistance to volume changes" and found that above a certain  $Ca^{+2}$  concentration (depending on alginate type) and with storage times that exceed a certain value, the gel beads are relatively stable to volume changes.

The simplest equation describing the time dependent swelling of a polymer matrix is a single-exponent power law model (Brazel & Peppas, 2000; Masaro & Zhu, 1999). Since the experimental data could not be fitted to this simple power law model, a second order equation was used. The time-dependent weight is expressed as (Valles, Durando, Katime, Mendizabal, & Puig, 2000):

$$\frac{t}{M_t} = \frac{1}{M_{eq}} \cdot t + \frac{1}{k \cdot M_{eq}^2} \quad (5)$$

where  $M_t$  is the polymer's weight at time  $t$ ,  $M_{eq}$  is its weight in equilibrium, and  $k$  is the second order swelling rate constant. As can be seen from the experimental data presented in Fig. 6, the swelling of the two alginate types at all  $CaCO_3$  concentrations obeys a second-order kinetics. This type of swelling kinetics was also observed for various polymer systems, such as acrylamide with itaconic acid or some of its esters (Valles et al., 2000),  $N$ -isopropylacrylamide-co-itaconic acid (Katime, Valderruten, & Quintana, 2001), gelatin (Wan, Wang, Cheng, & Yao, 2000), gelatins copolymers (Zheng,

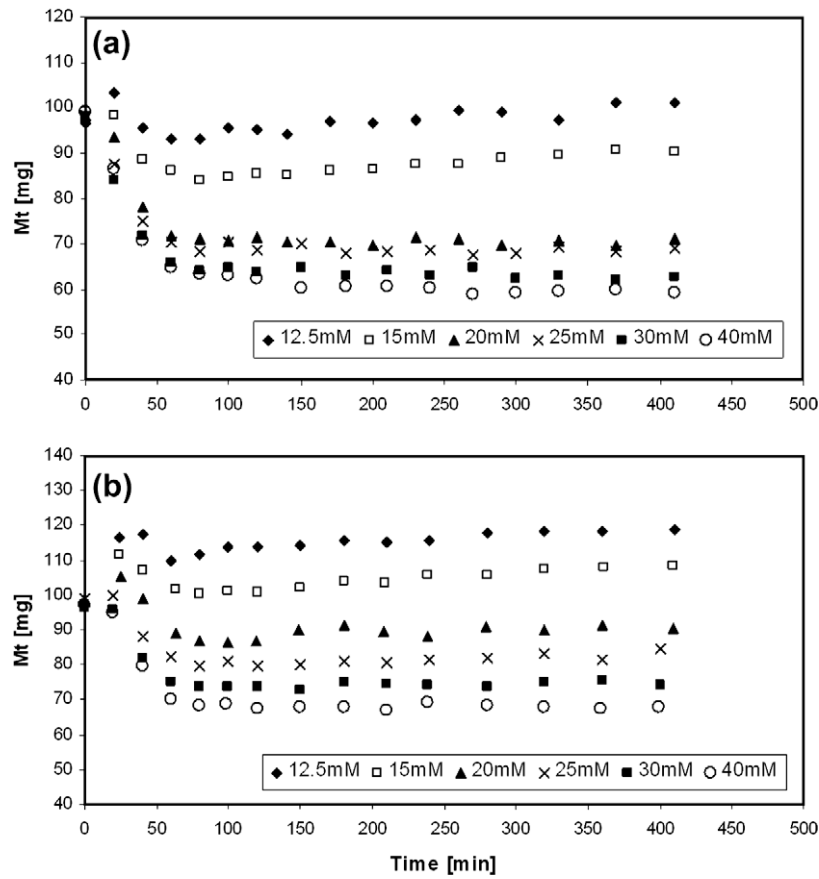


Fig. 5. Swelling kinetics of (a) LF200D and (b) HF120 alginate samples (5 mg/ml) cross-linked with different calcium concentrations.

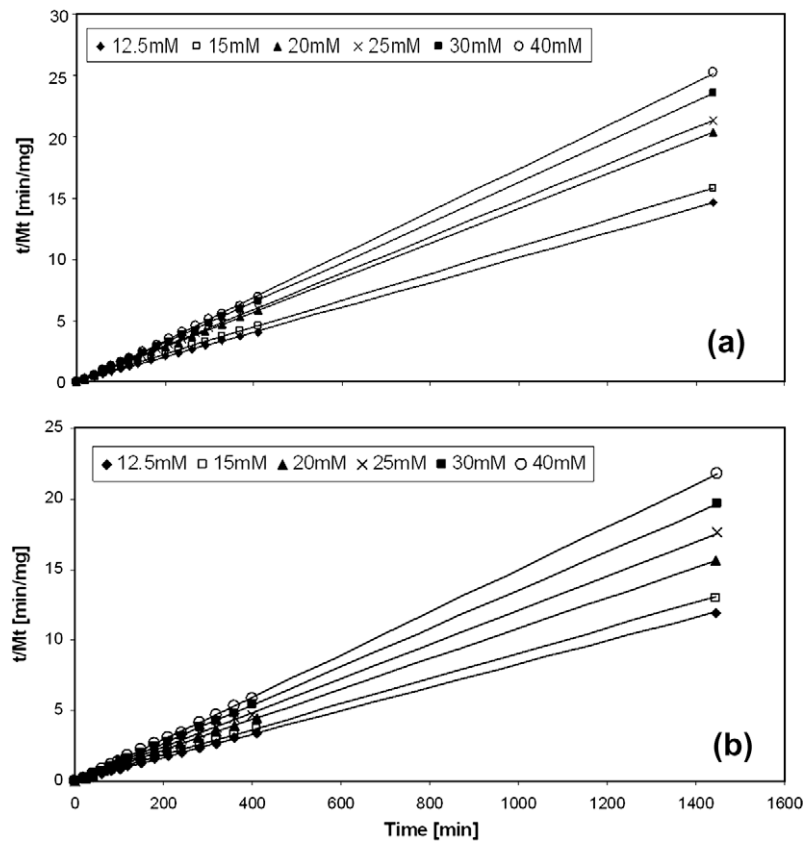


Fig. 6. Fits of the swelling data to second-order kinetics (a) LF200D and (b) HF120 alginate at different calcium concentration indicated by the legend.

**Table 4**

Fit parameters obtained from the swelling data presented in Fig. 6.

Ca [mM]	HF120 5 [mg/ml]				LF200D 5 [mg/ml]			
	Calculated $M_{eq}$ [mg]	$^*M_r$ [mg]	% error	$k$ [min mg] $^{-1}$	Calculated $M_{eq}$ [mg]	$^*M_r$ [mg]	% error	$k$ [min mg] $^{-1}$
12.5	120.48	120.75	0.060	0.0013	99.01	98.55	0.219	0.3692
15	111.11	110.74	0.124	0.0010	91.74	91.17	0.362	0.0017
20	92.59	92.53	0.004	0.0024	70.92	70.81	0.017	−0.0525
25	82.64	82.24	0.199	0.0200	67.57	67.42	0.032	−0.0039
30	73.53	73.55	0.001	−0.0055	60.98	61.09	0.020	−0.0024
40	66.23	66.29	0.006	−0.0028	56.82	57.08	0.120	−0.0018

\* Measured, after 24 h of swelling.

Gao, Wang, & Yao, 2005; Zheng, Wang, Gao, & Yao, 2005), poly(dimethylaminoethyl acrylate methyl chloride quaternary-co-itaconic acid) (Quintana, Valderruten, & Katime, 1999).

The fitted parameters are summarized in Table 4. The close agreement between the mass at equilibrium calculated from the fitting and the weight measured after 24 h of swelling, verify that alginate gels indeed reach equilibrium after 24 h of swelling. In general, the swelling rate constant decreases with an increase in the calcium concentration, indicating that the diffusion rate decreases at higher calcium concentrations. This suggests that the solvent diffusion at higher calcium concentrations is hindered due to steric obstacles caused by a lateral association leading to denser gel structure.

#### 4. Conclusions

The equilibrium swelling behavior of three different alginate types having different G contents were analyzed using known swelling theories developed for chemically cross-linked polymers. The experimental data suggests that these theories are not applicable for the studied alginate gels. In particular, an increase in the number of monomeric units between cross-links was observed at higher calcium concentration, whereas the theory predicts a decrease in the value of this parameter. It is suggested that lateral chain association reduced the number of junction zones thus leading to a decrease in the modulus.

The kinetics of the swelling process was analyzed using known swelling kinetics theories, and the samples were found to obey a second order equation. In addition, a decrease in the swelling rate constant with calcium concentration was observed. It is suggested that the diffusion rate is decreased due to steric distraction caused by the denser gel network created as a result of lateral chain association.

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